DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

CECW-EE

ETL 1110-2-549

Technical Letter
No. 1110-2-549

30 November 1997

Engineering and Design
RELIABILITY ANALYSIS OF NAVIGATIONAL LOCK
AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT

Distribution Restriction Statement

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RELIABILITY ANALYSIS OF NAVIGATIONAL LOCK AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT

1. Purpose

This engineer technical letter (ETL) provides guidance for assessing the reliability of mechanical and electrical systems of navigational locks and dams and for establishing an engineering basis for major rehabilitation investment decisions.

2. Applicability

This ETL applies to all USACE Commands having responsibilities for civil works navigational lock and dam projects.

3. References

ER 1130-2-500
Project Operations-Partners and Support (Work Management Policies)

EP 1130-2-500
Project Operations-Partners and Support (Work Management Guidance and Procedures)

EC 11-2-172
Annual Program and Budget Request for Civil Works Authorities, Corps of Engineers, FY99

ETL 1110-2-532
Reliability Assessment of Navigation Structures

ETL 1110-2-550
Reliability Analysis of Hydropower Equipment

MIL-STD-756B
Military Standard: Reliability Modeling and Prediction

American National Standards Institute/ANSI/ IEEE Std 493-1980
Design of Reliable Industrial and Commercial Power Systems

Bloch and Geitner 1994
Bloch, H. P., and Geitner, F. K. 1994. "Practical Machinery Management for Process Plants, Volume 2; Machinery Failure Analysis and Troubleshooting," Gulf Publishing Company, Houston, TX.

Green and Bourne 1972
Green, A. E., and Bourne, A. J. 1972. *Reliability Technology*, Wiley Interscience, London, New York.

Krishnamoorthi 1992
Krishnamoorthi, K. S. 1992. *Reliability Methods for Engineers*, ASQC Quality Press, Milwaukee, WI.

Mlakar 1994
Mlakar, P. F. 1994. "Reliability of Hydropower Equipment," Jaycor Report No. J650-94-001/1827, Vicksburg, MS.

Modarres 1993
Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis*, Marcel Dekker, Inc., New York.

Naval Surface Warfare Center 1992
Naval Surface Warfare Center. 1992. "Handbook of Reliability Prediction Procedures for Mechanical Equipment," NSWC-92/L01, Carderock Division, Dahlgren, VA.

Reliability Analysis Center 1994
Reliability Analysis Center. 1994. "NPRD Nonelectronic Parts Reliability Data, 1995," Rome, NY.

Sadlon 1993
Sadlon, R. 1993. "Mechanical Applications in Reliability Engineering," Reliability Analysis Center, Rome, NY.

4. Distribution Statement

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5. Background

a. Navigational lock and dam facilities are an important link in the nation's transportation system. Their mission is to maintain the navigable waterways and allow both cargo transport and recreational traffic between adjacent segments of the waterways. Mechanical and electrical components at these facilities function as systems to operate the various gates and valves. Breakdowns and poor performance of these systems can cause delays to navigation and adversely affect the overall national economy.

b. Lock and dam major rehabilitation projects began being budgeted under the Construction, General, and Flood Control, Mississippi River and Tributaries appropriation account in FY 93. To qualify as major rehabilitation projects, work activities must extend over two full construction seasons and the total required implementation costs must be greater than a certain minimum threshold. The threshold amounts are adjusted annually for inflation as published in the Annual Program and Budget Request, EC 11-2-172. To successfully compete as new starts, major rehabilitation proposals must be supported by the same level of economic analysis as new water resource projects. Chapter 3 of ER 1130-2-500 establishes policy for major rehabilitation at completed Corps projects. Chapter 3 of EP 1130-2-500 establishes guidance for the preparation and submission of major rehabilitation project evaluation reports for annual program and budget submissions.

c. The rehabilitation of mechanical and electrical equipment is usually included as part of the overall project. Mechanical and electrical component rehabilitation may include replacement and/or reconditioning to restore or improve a system to a like-new condition. The rehabilitation may be considered from various perspectives. It may be necessary to restore existing equipment that has deteriorated with time or failed in service, or equipment may become obsolete and replacement might be desired to upgrade the equipment to modern standards. The major rehabilitation evaluation reports and supporting information will have to provide evidence of criticality with a certain level of detail based on specific uniform engineering criteria. Reliability assessments based on probabilistic methods provide more consistent results and reflect both the condition of existing equipment and the basis for design.

d. Further guidance for the reliability evaluation of hydropower equipment has been published in ETL 1110-2-550 and Mlakar (1994). Guidance for the reliability assessment of navigation structures is included in ETL 1110-2-532.

6. Reliability Concepts and Definition of Terms

a. *Definition of terms.*

(1) Component. A piece of equipment or portion of a system which is viewed as an independent entity for purposes of evaluation; i.e., its reliability does not influence the reliability of another component.

(2) System. An orderly arrangement of components that interact among themselves and with external components, other systems, and human operators to perform some intended function.

(3) Failure. Any trouble with a component that causes unsatisfactory performance of the system.

(4) Hazard function or failure rate. The instantaneous probability of failure of an item in the next unit of time given that it has survived up to that time. It is the mean number of failures of a component per unit exposure time.

(5) Reliability. The probability that an item will perform its intended function under stated conditions, for either a specified interval or over its useful life.

(6) Basic reliability. Basic reliability measures the demand for maintenance and logistic support of a system caused by an item's unreliability.

(7) Mission reliability. Reliability as a measure of operational effectiveness of a system. A mission reliability prediction estimates the probability that items will perform their required functions during a mission.

(8) Unsatisfactory performance. Sub-standard operation; partial or complete shutdown of the system; operation of safety devices; unexpected deenergization of any process or equipment.

b. *Measures of component reliability*

(1) Reliability function. The continuous probabilistic approach to item reliability is represented by the reliability function. It is simply the probability that an item has survived to time *t*. The mathematical expression can be summarized by:

$$R(t) = P(T \geq t) \qquad (1)$$

where

t = the designated period of time for the item's operation

T = time to item failure

$P(T \geq t)$ = probability that the time to failure of an item will be greater than or equal to its service time

$R(t)$ = reliability of the item, i.e. probability of success

Conversely, the probability of failure $F(t)$ is simply:

$$F(t) = 1 - R(t) \qquad (2)$$

(2) Hazard function or failure rate. The hazard function $h(t)$ represents the proneness to failure of a component as a function of its age or time in operation. It reflects how the reliability of a component changes with time as a result of various factors such as the environment, maintenance, loading, and operating condition. From the reference literature, it can be shown that:

$$h(t) = \frac{f(t)}{R(t)} \qquad (3)$$

where

$f(t)$ = Probability density function (pdf). It is the limiting curve of the relative frequency of occurrences of a particular random variable as the sample approaches infinity.

The hazard function or instantaneous failure rate is the conditional probability of failure of an item in the next unit of time given that it has survived up to that time. The hazard function can increase, decrease, or remain constant. It has been shown that the failure rate behavior of most mechanical and electrical engineering devices follows that shown in Figure 1. This is known as the *bathtub curve*. Region A represents a high initial failure rate which decreases with time to nearly constant. This is known as the infant mortality region and is a result of poor workmanship or quality control. Region B represents the useful life phase. Here, failures occur because of random events. Region C represents the wearout phase where failures occur due to complex aging or deterioration.

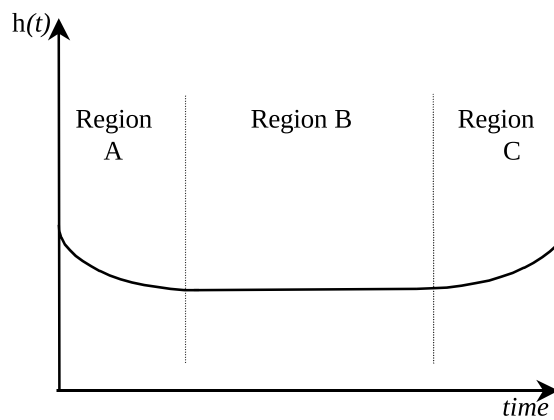


Figure 1. Typical Bathtub Curve

The flat random or chance failure region (Region B) of the curve for electromechanical devices is much longer than the other two regions. Electrical devices exhibit a much longer chance failure period relative to mechanical devices. Methods presented in this document will attempt to determine reliability and predict the characteristics of Regions B and C of the bathtub curve for mature equipment using the common continuous distribution functions discussed in the next sections. The infant mortality region (Region A) will not be directly discussed in this ETL since the equipment considered for major rehabilitation projects usually falls in Regions B or C.

(3) Exponential distribution. Exponential distribution is the most commonly used distribution in reliability analysis. The reliability function is:

$$R(t) = e^{-\lambda t} \qquad (4)$$

where

t = time

λ = failure rate

This distribution can be used to represent the constant hazard rate region (Region B) of the bathtub curve. The hazard function for the exponential distribution remains constant over time and is represented as simply λ:

$$h(t) = \lambda \tag{5}$$

Plots of the reliability and hazard functions for the exponential distribution are shown in Figures 2 and 3.

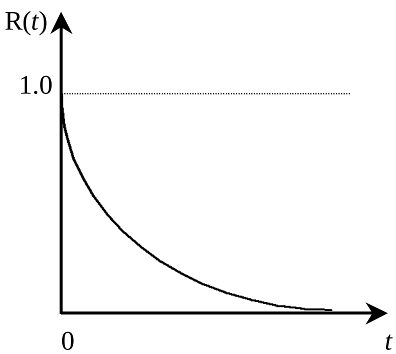


Figure 2. Reliability Function for Exponential Distribution

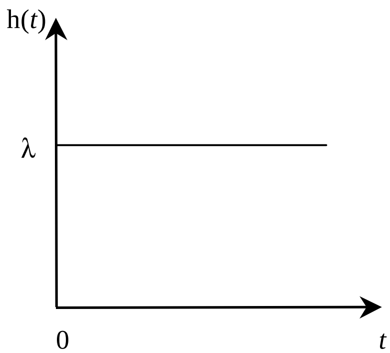


Figure 3. Hazard Function for Exponential Distribution

The average or mean of the exponential life distribution is the mean time to failure (MTTF). It is the average length of life of all units in the population. It has significance in that the reciprocal of the hazard rate is equal to the MTTF:

$$\text{MTTF} = \frac{1}{\lambda} \tag{6}$$

(4) Weibull distribution. The Weibull distribution is a generalization of the exponential distribution. This distribution covers a variety of shapes and its flexibility is useful for representing all three regions of the bathtub curve. The Weibull distribution is appropriate for a system or complex component made up of several parts. The Weibull reliability function is:

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{7}$$

where

α = the scale parameter or characteristic life

β = the shape parameter

For $0 < \beta < 1$, the Weibull distribution characterizes wear-in or early failures. For $\beta = 1$, the Weibull distribution reduces to the exponential distribution. For $1 < \beta < \infty$, the Weibull distribution characterizes the wear-out characteristics of a component (increasing hazard rate). The Weibull hazard function is:

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{8}$$

Plots of the reliability and hazard functions for the Weibull distribution are shown in Figures 4 and 5.

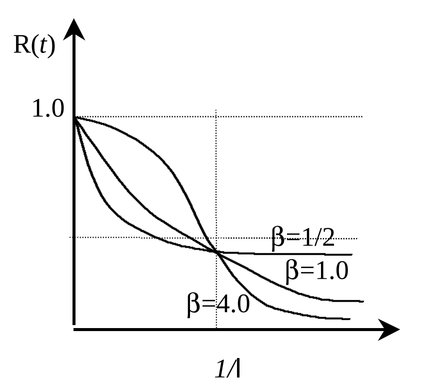


Figure 4. Reliability Function for Weibull Distribution

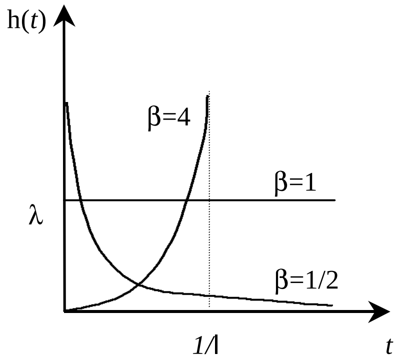


Figure 5. Hazard Function for Weibull Distribution

c. *General data required*. Reliability analyses provide the best estimate of the reliability anticipated from a given design within the data limitations and to the extent of item definitions. The required data are dependent on the availability and depth of analysis required. Mechanical and electrical components are typically complex and made up of many different parts, each with several modes of failure. These failure modes are associated with many ambiguous variables such as operating environment, lubrication, corrosion, and wear. Historic data for lock and dam equipment is not usually available nor is it collected by controlled and tested means. These deficiencies require the analysis of equipment to be completed through the use of data from larger systematic samples of similar equipment such as the published failure rate data source of the Reliability Analysis Center (1994). Failure rate data can also be obtained by multivariate methods developed in the "Handbook of Reliability Prediction Procedures for Mechanical Equipment" (Naval Surface Warfare Center 1992). Prior to any reliability determination, investigations should be conducted to gain a thorough knowledge of the mechanical and electrical requirements and layouts, to identify equipment deficiencies, and to learn the project history and future demands.

7. Engineering Reliability Analysis

Assessing the reliability of a system from its basic elements is one of the most important aspects of reliability analysis. As defined, a system consists of a collection of items (components, units, etc.) whose proper, coordinated function leads to its proper operation. In a reliability analysis, it is therefore important to model the reliability of the individual items as well as the relationship between the various items to determine the reliability of the system as a whole. This ETL applies the reliability block diagram (RBD) method as outlined in MIL-STD-756B to model conventional probability relationships of collections of *independent* components and systems.

8. System Reduction

Determining the number of discrete mechanical and electrical components in a lock and dam requires system reduction to reduce the vast complexity of numerous components into smaller groups of critical components. Reliability models should be developed to the level of detail for which information is available and for which failure rate (or equivalent) data can be applied. Functional elements which are not included in the mission reliability model shall be documented and rationale for their exclusion shall be provided.

9. Component Reliability

The failure distribution appropriate to the specific electronic, electrical, electromechanical, and mechanical items should be used in computing the component reliability. In most cases, the failure distribution will not be known and the exponential or the Weibull function may be assumed. The α and β parameters of the Weibull equation are normally empirically determined from controlled test data or field failure data. This ETL presents a procedure for estimating these values. If the β value in the Weibull function is unknown, a value of 1.0 should be assumed. The flat failure region of mechanical and electrical components is often much longer than the other two regions, allowing this assumption to be adequate. Once the component reliability values are determined, the RBD method is used to evaluate their relationship within the system to determine the total system reliability. Appendices C and D contain more information on determining component reliability.

10. System Risk Analysis Using Block Diagrams

The necessity for determining the reliability of a system requires that the reliability be considered from two perspectives, basic reliability and mission reliability. Both are separate, but companion, products which are essential to adequately quantify the reliability of a system. The incorporation of redundancies and alternate modes of operation to improve mission reliability invariably decreases basic reliability. A decrease in basic reliability increases the demand for maintenance and support. Basic reliability is normally applied to evaluate competing design alternatives.

a. Basic reliability - series system model. A basic reliability prediction is a simplified model that is intended to measure overall system reliability. It is used to measure the maintenance and logistic support burden required by the system. A basic reliability model is an all-series model. Accordingly, all elements providing redundancy or parallel modes of operation are modeled in series. In a series system, the components are connected in such a manner that if any one of the components fail, the entire system fails. Care should be taken when developing this type of model since the final value of the basic reliability of the system is inversely proportional to the number of components included in the evaluation; i.e., the more components there are, the lower the reliability. Such a system can be schematically represented by an RBD as shown in Figure 6.

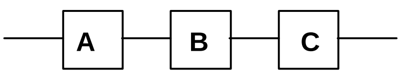


Figure 6. Series System

For a system with N mutually *independent* components, the system reliability for time t is:

$$R_S(t) = R_A(t) * R_B(t) * R_C(t) * \ldots * R_N(t) \qquad (9)$$

It can also be shown that if $h_s(t)$ represents the hazard rate of the system, then:

$$h_s(t) = \sum_{i=1}^{n} h_i(t)$$

(10)

The failure rate of a series system is equal to the sum of the failure rates of its components. This is true regardless of what the failure distributions of the components are.

b. Mission reliability. The mission reliability model utilizes the actual system configuration to measure the system capability to successfully accomplish mission objectives. The mission reliability model may be series, parallel, standby redundant, or complex. An example of lock and dam mission reliability is given in Appendix B.

(1) *Parallel system model.* In a parallel system, the system fails only when all of the components fail. Such a system is represented in Figure 7. In this configuration, the system will still perform if at least one of the components is working.

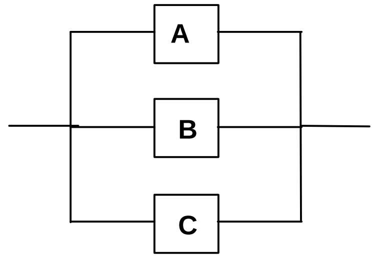


Figure 7. Parallel System

The reliability for the system is given by:

$$R_S(t) = 1-(1-R_A(t))(1-R_B(t))(1-R_C(t)) \qquad (11)$$

or

$$R_S(t) = 1 - \prod_{i=1}^{N} (1 - R_i(t)) \qquad (12)$$

A more general form of a parallel system is the "*r* out of *n*" system. In this type of system, if any combination of *r* units out of *n independent* units arranged in parallel work, it guarantees the success of the system. If all units are *identical,* which is often the case, the reliability of the system is a binomial summation represented by:

$$R_S(t) = \sum_{j=r}^{n} \binom{n}{j} R(t)^j (1 - R(t))^{n-j} \qquad (13)$$

where

$$\binom{n}{j} = \frac{n!}{j!(n-j)!} \qquad (14)$$

The hazard rate for parallel systems can be determined by using:

$$h_s(t) = \frac{-d \ln R_s(t)}{dt} \qquad (15)$$

or

$$h_s(t) = \frac{-d \ln[1 - \prod_{i=1}^{N} (1 - R_i(t))]}{dt} \qquad (16)$$

The result of $h_s(t)$ becomes rather complex and the reader is referred to the reference literature.

(2) *Standby redundant system.* A two-component standby redundant system is shown in Figure 8. This system contains equipment that is in primary use and also equipment standing idle ready to be used. Upon failure of the primary equipment, the equipment standing idle is immediately put into service and switchover is made by a manual or automatic switching device (SS).

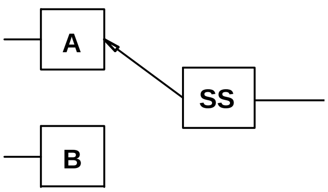


Figure 8. Standby Redundant System

The system reliability function for the exponential distribution can be calculated for a two-component, standby redundant system using the following equation:

$$R_S(t) = R_A(t) + \frac{(\lambda_A R_B(t))}{(\lambda_A + \lambda_{SS} + \lambda'_B - \lambda_B)} \left[1 - \exp(-(\lambda_A + \lambda_{SS} + \lambda'_B - \lambda_B) d_i t)\right] \quad (17)$$

where

d_i = duty factor for respective failure rate

λ'_B = hazard rate of the standby equipment while not in use

(3) *Complex system models.* Complex systems can be represented as a series-parallel combination or a non-series-parallel configuration. A series-parallel RBD is shown in Figure 9. This type of system is analyzed by breaking it down into its basic parallel and series modules and then determining the reliability function for each module separately. The process can be continued until a reliability function for the entire system is determined. The reliability function of Figure 9 would be evaluated as follows:

$$R_1(t) = [\,1 - [(1 - R_{A1}(t))\,(1 - R_{B1}(t))\,(1 - R_{C1}(t))]] * R_{D1}(t) \quad (18)$$

$$R_2(t) = [\,1 - [(1 - R_{A2}(t))\,(1 - R_{B2}(t))]] * R_{D2}(t) \quad (19)$$

$$R_S(t) = [\,1 - [(1 - R_1(t))\,(1 - R_2(t))]] \quad (20)$$

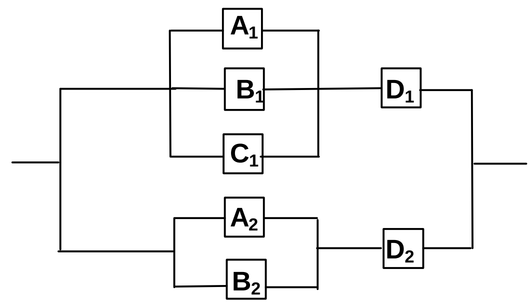


Figure 9. Series-Parallel System

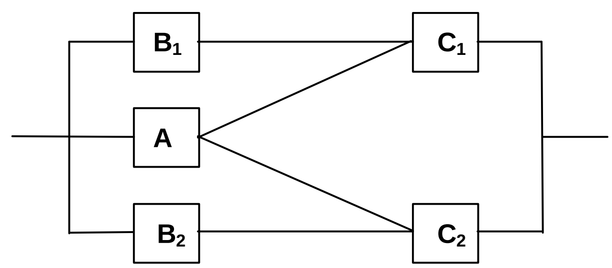


Figure 10. Non-series-parallel system

A non-series-parallel system is shown in Figure 10. One method of analyzing non-series-parallel systems uses the following general theorem:

$$R_S(t) = R_S(\text{if X is working})\, R_X(t) + R_S(\text{if X fails})\,(1 - R_X(t)) \quad (21)$$

The method lies in selecting a critical component (X) and finding the conditional reliability of the system with and without the component working. The theorem on total probability is then used to obtain the system's reliability (see Appendix A).

11. Recommendations

It is recommended that the procedures contained herein be used as guidance toward assessing the reliability of mechanical and electrical equipment for navigational locks and dams. It shall be used to quantify reliability and risk for decision analysis so that upgrade or rehabilitation alternatives can be evaluated.

12. Additional Information

Much of the work covered by this ETL is still under development. The latest information pertaining to the work described herein can be obtained from CECW-EE. Reliability-related Internet web sites are listed in Appendix E.

FOR THE DIRECTOR OF CIVIL WORKS:

STEVEN L. STOCKTON, P.E.
Chief, Engineering Division
Directorate of Civil Works

5 Appendices
APP A - Non-Series-Parallel System Analysis
APP B - Example of Lock and Dam Mission Reliability
APP C - Mechanical Equipment Example
APP D - Electrical Equipment Example
APP E – Reliability-Related Internet Web Sites

APPENDIX A: NON-SERIES-PARALLEL SYSTEM ANALYSIS

A complex system that is neither in series nor parallel is shown in Figure A-1. The reliability is evaluated using the theorem on total probability:

$R_S(t) = R_S(\text{if X is working})\ R_X(t) + R_S$ (if X fails) $(1 - R_X(t))$ (A-1)

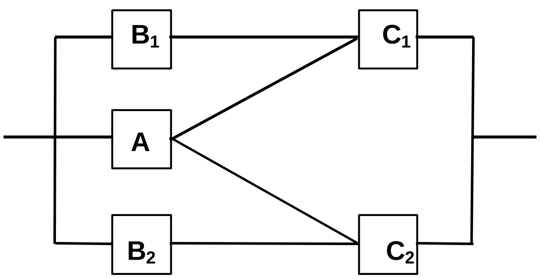


Figure A-1. A Non-series-parallel System

Select a critical component. In this case, select component A. The system can function with or without it and in each case the system resolves into a simpler system that is easily analyzed. If A works, it does not matter if B_1 or B_2 are working. The system can then be represented by the reliability block diagram (RBD) in Figure A-2.

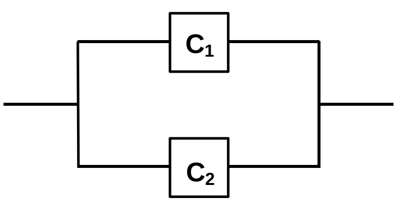


Figure A-2. Reduction of System with Component A Working

If component A does not work, the system can be reduced to Figure A-3.

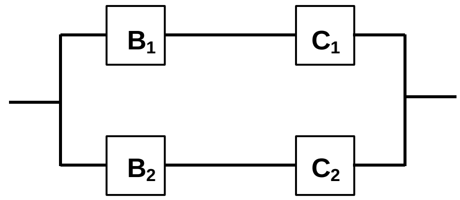


Figure A-3. Reduction of System with Component A not Working

Figure A-2 is evaluated as follows:

$R_S(\text{if A is working}) = 1 - [(1 - R_{C1}(t))$ $(1 - R_{C2}(t))]$ (A-2)

Figure A-3 is resolved as:

$R_S(\text{if A fails}) = 1 - [(1 - (R_{B1}(t) * R_{C1}(t)))$ $(1 - (R_{B2}(t) * R_{C2}(t)))]$ (A-3)

The total system reliability becomes:

$R_S(t) = R_S(\text{if A is working})\ R_A(t) + R_S$ (if A fails) $(1 - R_A(t))$ (A-4)

APPENDIX B: EXAMPLE OF LOCK AND DAM MISSION RELIABILITY

B-1. Description

The typical lock and dam that was evaluated is located on the Mississippi River. The lock is 182.88 m (600 ft) long and 33.53 m (110 ft) wide with four miter gates and four tainter valves. The dam is 411.48 m (1350 ft) long with 14 tainter gates. Each miter gate and valve is operated by an electric motor-driven gear train system. Each dam gate is also operated by an electric motor-driven gear train system. The electrical control system consists of hardwired relaying. Electrical power to the lock and dam is provided by an incoming utility line or a 300-kw diesel standby generator through an automatic transfer switch. The dam electrical power is fed from the lock distribution through two redundant feeders.

In 1990, the lock gate and valve machinery and all electrical systems were replaced. The dam machinery is the original equipment installed when the dam was built in 1936. In this example, the mechanical and electrical subsystem reliability values from Appendices C and D were applied to the overall system to determine an overall lock and dam system mechanical and electrical reliability value.

B-2. Lock and Dam Mission and Function Definitions

The lock and dam system reliability block diagrams were formulated by defining the facility mission. The mission of this lock and dam system is to maintain a navigable pool and pass traffic between adjacent pools. This mission was considered to be met when the pool is navigable and traffic is not impeded from passing through the lock for more than 4 hr. This value was considered appropriate for this site. This limit may vary depending on the different site conditions.

The layout and operation of the mechanical and electrical (M/E) systems were first evaluated to identify the critical subsystems whose failure could result in unsatisfactory performance of the overall lock and dam system. For this example, it was determined by consultation with hydraulic and operations personnel that the mission to maintain pool would be met at this site if at least four dam gates are operable. Similarly, it was found that the mission to pass traffic would be met if all lock gates, one upper valve, and one lower valve were operable.

The subsystems which transmit power and/or force to these gates were considered critical to the mission and were included in the reliability analysis. Gate and valve control system components were not considered critical because failed control components can typically be repaired or bypassed within the 4 hr timeframe defined to meet the mission. Lighting, building utilities, water pumps, and other M/E appurtenances were considered to be similarly ancillary to meeting the mission.

From the evaluation of the M/E system layout and operation, a list of functions was developed which would result in probable unsatisfactory performance of the lock and dam system. These functions are listed in Table B-1.

Table B-1
Mission Functions

Lock (L) functions:
LA - Both incoming utility power and the standby generator fail.
LB - The transfer switch fails to operate.
LC - The main switchboard fails in any critical area.
LD - Any one gate fails to operate.
LE - Both upper or both lower valves fail to operate.
Dam (D) functions:
DD - Electrical distribution to the dam fails in any critical area.
DE - More than 10 gates fail to operate.

Using these functions, the components and subsystems critical to the success of the mission were extracted along with their relationship within the lock and dam system. The major components or subsystems were then organized into the reliability block diagram.

B-3. Basic Reliability Block Diagram

Since no design alternatives were being evaluated, the basic reliability values for mechanical and electrical systems of navigational locks and dams were not considered. However, the basic reliability could easily be modeled and calculated by constructing an all-series block diagram and multiplying the individual reliability values to obtain an overall basic reliability value.

B-4. Mission Reliability Block Diagram

The mission reliability block diagram was organized by relating the function of the components or subsystems with the successful completion of the mission. For successful completion of the mission, both the lock and dam must operate satisfactorily. This is represented by a series arrangement. The initial mission reliability block diagram is shown in Figure B-1 where block L represents the lock equipment and block D represents the dam equipment.

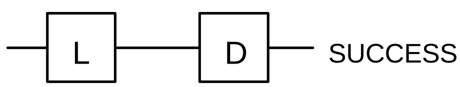


Figure B-1. Initial mission reliability diagram

The basic blocks of Figure B-1 were broken down into the critical equipment associated with the functions listed in Table B-1. They are:

LA1 = Utility service entrance
LA2 = Generator service
LB = Transfer switch
LC = Switchboard bus
LD1 = Upper left lock gate equipment
LD2 = Upper right lock gate equipment
LD3 = Lower left lock gate equipment
LD4 = Lower right lock gate equipment
LE1 = Upper left valve equipment
LE2 = Lower left valve equipment
LE3 = Upper right valve equipment
LE4 = Lower right valve equipment
DD1 = Dam distribution feeder No. 1
DD2 = Dam distribution feeder No. 2
DE# = Dam gate No. equipment

a. Lock block diagram. The electrical distribution is comprised of two power sources, the electric utility service entrance (LA1) and the generator service (LA2), with service or feeder conductors and circuit breakers, an automatic transfer switch (LB), and a switchboard bus (LC). The power sources are "stand-by redundant" because the system continues to operate successfully if either one of the sources operate (as long as the transfer switch operates). The resulting electrical distribution subsystem diagram for the lock and dam was organized as shown in Figure B-2.

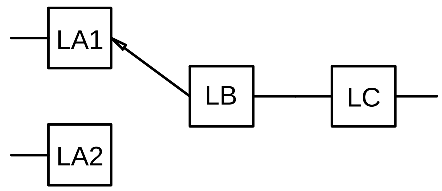


Figure B-2. Electrical distribution block diagram

The M/E equipment for all four lock gates must operate properly for satisfactory performance of the lock and dam system. As a result, the miter gate system blocks (LD1, LD2, LD3, and LD4) were organized in a simple series. The valve equipment blocks (LE1, LE2, LE3, and LE4) were modeled as a complex non-series-parallel system because of the requirement for the operation of at least one of two upper valves and one of two lower valves at all times for success of the mission. Figure B-3 is the lock gate and valve block diagram.

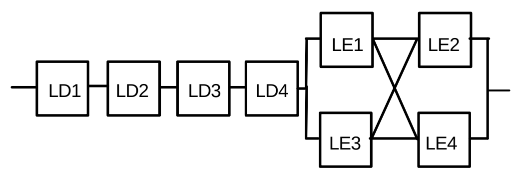


Figure B-3. Lock reliability block diagram

b. Dam block diagram. The dam has two parallel electrical feeders (DD1 and DD2) consisting of circuit breakers and conductors. Figure B-4 is the parallel block diagram.

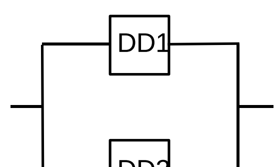
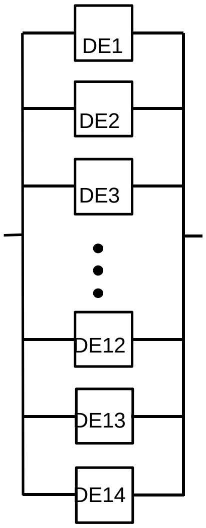


Figure B-4. Dam feeders

The dam feeders are connected to 14 identical dam gate subsystems operating in parallel as shown in Figure B-5. For mission success, at least four gates must be operable. The resulting system is an "*r* out of *n*-system" where 4 of the 14 gate blocks must work for system success.



(4 of 14 must function)

Figure B-5. Dam gate block diagram

The entire reliability block diagram for the lock and dam system is shown in Figure B-6 on page B-4.

B-5. Mission Reliability of the Lock and Dam Mechanical and Electrical Equipment

The numerous lock and dam gate and valve blocks (LD#, LE#, DE#) of the mission reliability block diagram were expanded into a series configuration of mechanical (M) and electrical (E) subsystems as shown in Figure B-7. There is no mechanical equipment associated with the electrical distribution system and dam feeder system.

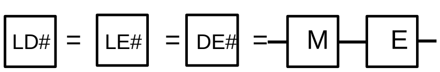


Figure B-7. Gate and valve block diagram

The mechanical (M) and electrical (E) subsystems were evaluated separately, as shown in Appendices C and D. The subsystem values were taken from Tables C-3, C-4, D-1, D-2, D-3, D-4, and D-5 for an arbitrary year (2000) and consolidated as shown in Table B-2. The mechanical and electrical subsystem values for each item in columns 2 and 3 were multiplied together as a series system to obtain a single value in column 4.

a. Lock reliability. The lock electrical distribution subsystem was evaluated as a standby redundant system as follows:

$$R_{\text{Lock Elec. Dist.}} = \left[R_{LA1}(t) + \frac{\lambda_{LA1} R_{LA2}(t)}{(\lambda_{LA1} + \lambda_{LB} - \lambda_{LA2})}[1 - R]\right] * R_{LC}(t) \quad \text{(B-1)}$$

where

$$R = \exp(-(d_{LA1}\lambda_{LA1} + d_{LB}\lambda_{LB} - d_{LA2}\lambda_{LA2})(t))$$

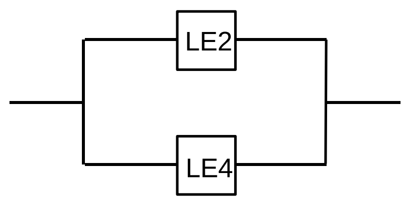
The reliability for the standby generator in standby mode is assumed to be 100 percent since the generators typically receive exceptional maintenance; therefore,

$$\lambda'_{LA2} = 0. \quad \text{(B-2)}$$

The lock gates' subsystem reliability was evaluated as a simple series system as follows:

$$R_{\text{Lock Gates}} = R_{LD1} * R_{LD2} * R_{LD3} * R_{LD4} \quad \text{(B-3)}$$

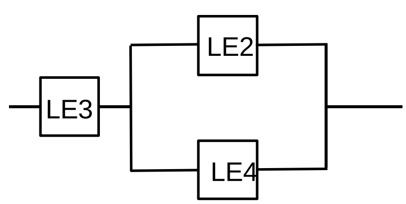
b. Lock valve reliability. Lock valve subsystem reliability was evaluated using the method presented in Appendix A. If LE1 works, it does not matter if LE3 works and the block diagram becomes:



so,

$$R_{\text{LE1 Working}} = 1-(1-R_{LE2})(1-R_{LE4}) \quad \text{(B-4)}$$

If LE1 does not work, then

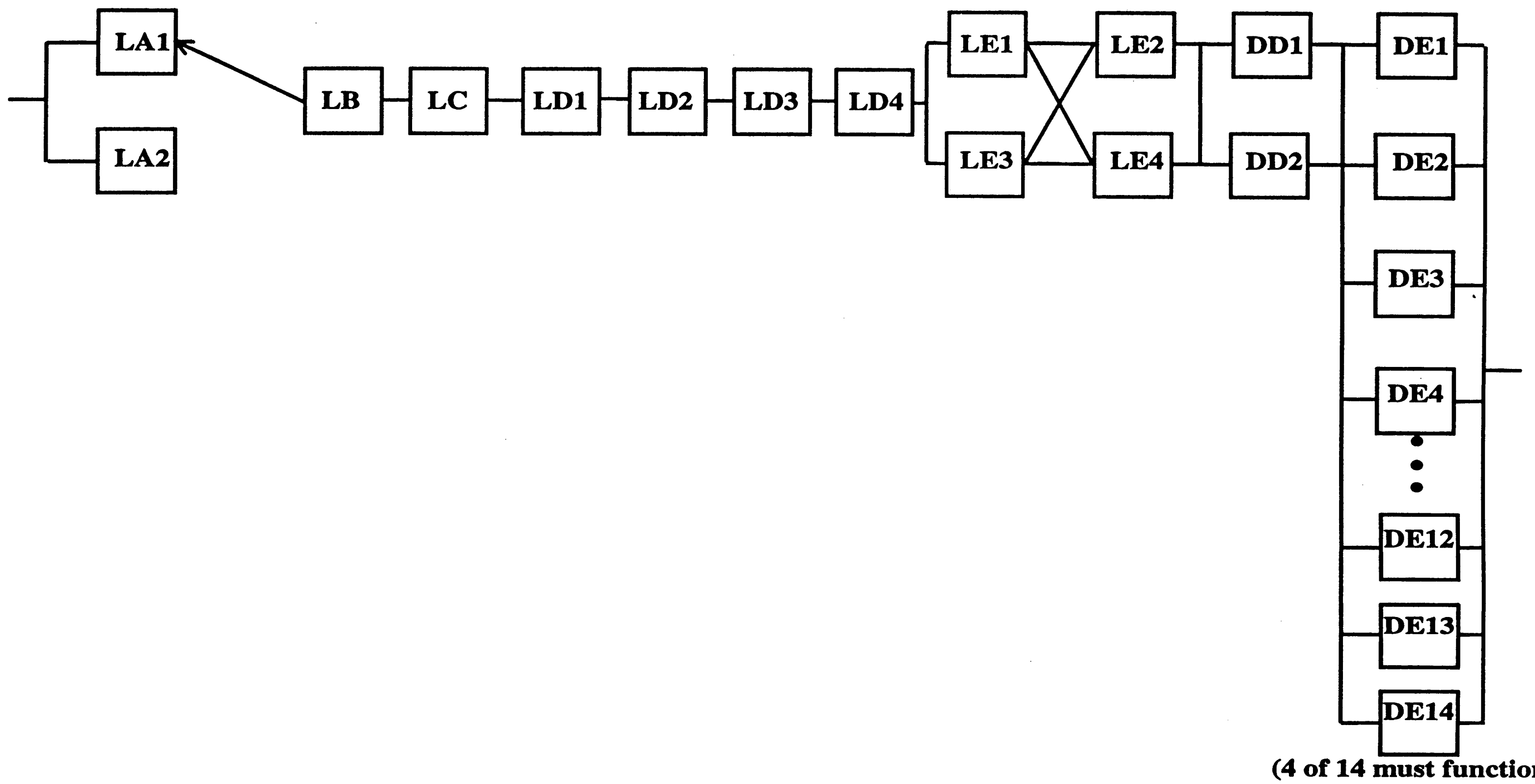


and

$$R_{\text{LE1 not Working}} = R_{LE3}*[1-(1-R_{LE2})(1-R_{LE4})] \quad \text{(B-5)}$$

The reliability expression becomes:

$$R_{\text{Lock Valves}} = [1-(1-R_{LE2})(1-R_{LE4})]*R_{LE1} + [R_{LE3}*[1-(1-R_{LE2})(1-R_{LE4})]]*(1-R_{LE1}) \quad \text{(B-6)}$$



LA1 - Utility service entrance
LA2 - Generator service
LB - Transfer switch
LC - Switchboard bus
LD# - Lock Gates 1 - 4 (mechanical and electrical)
LE# - Lock Valves 1 - 4 (mechanical and electrical)

DD1 - Dam feeder 1
DD2 - Dam feeder 2
DE# - Dam gate # (mechanical and electrical)

Figure B-6. Lock and dam mechanical and electrical mission reliability block diagram *c. Dam reliability.* The dam feeders were evaluated as a parallel system according to:

$$R_{Dam\ Dist.} = [1 - (1 - R_{DD1})\ (1 - R_{DD2})] \qquad (B\text{-}7)$$

The individual gate reliability values are identical as given in column 4 of Table B-2. The combined system reliability of the dam gates, consisting of a "4 out of 14" paralleled gate system was evaluated according to the following formula:

$$R_{Dam\ Gates} = \sum_{j=4}^{14} \binom{14}{j} R_{DE}^{\ j}\,(1 - R_{DE})^{14-j} \qquad (B\text{-}8)$$

d. Overall M/E mission reliability. The overall lock and dam M/E mission reliability value in the last Column of Table B-2 is computed from a series arrangement where,

$$R_{Overall\ Lock\ and\ Dam} = R_{Lock\ Elec.\ Dist.} * R_{Lock\ Gates} * R_{Lock\ Valves} * R_{Dam\ Distribution} * R_{Dam\ Gates} \qquad (B\text{-}9)$$

The mechanical and electrical mission reliability for the lock and dam of this example is calculated to be approximately 30 percent. In other words, there is a 70-percent chance that a component within the mechanical/electrical system will fail, which will cause a shutdown of 4 hr or more in the 10-year period from 1990-2000. The mission reliability of this lock and dam is impacted by the relatively low reliability (0.4366) of the lock gates subsystem. The dam, due to its small duty cycle and multiple redundancy to complete the mission, is found to least influence the mission reliability.

Table B-2
Lock and Dam Mechanical and Electrical Mission Reliability for Year 2000

Symbol	Mechanical Subsystem Reliability (M)	Electrical Subsystem Reliability (E)	Mech./Elec. (M*E)	Lock Electrical Distribution	Lock Gates Subsystem	Lock Valves Subsystem	Dam Distribution	Dam Gates Subsystem	Lock and Dam Mission Reliability
LA1/LA2/LB/ LC		0.7631	0.7631	0.7631					
LD1	0.8657	0.9389	0.8129						
LD2	0.8657	0.9389	0.8129						
LD3	0.8657	0.9389	0.8129						
LD4	0.8657	0.9389	0.8129	----------	---0.4366				
LE1	0.8311	0.9389	0.7803						
LE2	0.8311	0.9389	0.7803						
LE3	0.8311	0.9389	0.7803						
LE4	0.8311	0.9389	0.7803	----------	----------	--0.9058			
DD1		0.8890	0.8890			.			
DD2		0.8890	0.8890	----------	----------	----------	-0.9877		
DE1	0.8149	0.9879	0.8051						
DE2	0.8149	0.9879	0.8051						
DE3	0.8149	0.9879	0.8051						
DE4	0.8149	0.9879	0.8051						
DE5	0.8149	0.9879	0.8051						
DE6	0.8149	0.9879	0.8051						
DE7	0.8149	0.9879	0.8051						
DE8	0.8149	0.9879	0.8051						
DE9	0.8149	0.9879	0.8051						
DE10	0.8149	0.9879	0.8051						
DE11	0.8149	0.9879	0.8051						
DE12	0.8149	0.9879	0.8051						
DE14	0.8149	0.9879	0.8051	----------	----------	----------	----------	-1.0000	
									0.2981

Formula Summary

$$R_{\text{Lock Elec. Dist.}} = R_{\text{Lock Elec. Dist.}} = \left[R_{LA1}(t) + \frac{\lambda_{LA1} R_{LA2}(t)}{(\lambda_{LA1} + \lambda_{LB} - \lambda_{LA2})}\left[1 - \exp(-(d_{LA1}\lambda_{LA1} + d_{LB}\,\lambda_{LB} - d_{LA2}\lambda_{LA2})(\,t))\right]\right] * R_{LC}(t)$$

$$R_{\text{Lock Gates}} = R_{LD1} * R_{LD2} * R_{LD3} * R_{LD4}$$

$$R_{\text{Lock Valves}} = [1-(1-R_{LE2})(1-R_{LE4})]*R_{LE1}+[R_{LE3}*[1-(1-R_{LE2})(1-R_{LE4})]]*(1-R_{LE1})$$

$$R_{\text{Dam Dist.}} = [1 - (1 - R_{DD1})\,(1 - R_{DD2})]$$

$$R_{\text{Dam Gates}} = \sum_{j=4}^{14} \binom{14}{j} R_{DE}{}^{j}\,(1- R_{DE})^{14-j}$$

$$R_{\text{Overall Lock and Dam}} = R_{\text{Lock Elec. Dist.}} * R_{\text{Lock Gates}} * R_{\text{Lock Valves}} * R_{\text{Dam Distribution}} * R_{\text{Dam Gates}}$$

APPENDIX C: MECHANICAL EQUIPMENT EXAMPLE

C-1. Description

For this analysis, the individual mechanical gate systems are considered subsystems to the overall lock and dam system. The example lock miter gate and valve machinery subsystems are laid out as shown in Figures C-1 and C-3. The dam gate machinery is laid out as shown in Figure C-5.

C-2. Reliability Block Diagram Formulation

Formulation of the system reliability block diagram (RBD) is in accordance with MIL-STD-756B. The initial step in determining the reliability of the mechanical systems of the lock and dam is to identify the function or mission of the machinery. The machinery function is to operate the gates. The major components required for mission success are defined and organized into an RBD. The block diagrams for the miter gate and tainter valve and dam gate components included in this evaluation are shown in Figures C-2, C-4, and C-6. The RBD is simplified or expanded, if necessary, to sufficient detail to allow determination of component failure rate from published data. The process continues until only blocks with published component failure rate data remain in the block reliability model. In this example, the structural supports are not included in the model. They are unique to each system and published data are not available. For the lock and dam gate and valve machinery shown below, the failure of any one component constitutes nonperformance of the mission. There are no parallel or redundant items. The mission and basic block diagrams will be series models.

C-3. Reliability Calculation

The basic and mission reliability model blocks should be keyed with consistent nomenclature of elements. Each model should be capable of being readily updated with new information resulting from relevant tests, as well as any changes in item configuration or operational constraints. Hardware or functional elements of the system which are not included in the model shall be identified. Rationale for each element's exclusion from the model shall be provided.

a. Duty cycle. The mission or function of the system should address the duty cycle or period of operation. The miter gate equipment is considered to have a negligible failure rate during periods of non-operation (ignoring barge impact). The failure rate can be modified by a duty cycle factor. The duty cycle factor is the ratio of actual operating time to total mission time t. For example, the equation $R(t) = e^{-\lambda td}$ is the exponential failure rate distribution with a duty factor d. The lock equipment in this example has an average number of 13,148 open/close cycles per year. Assuming the operating time of an open or close operation is 120 sec (or 240 sec per open/close cycle) and using a total mission time of 50 years, then,

$$\text{Operating time} = (240*13\,148)/3600$$

$$= 877 \text{ operational hr per year} * 50 \text{ years} \quad \text{(C-1)}$$

$$= 43\,850 \text{ hr} = 5 \text{ years}$$

For t = 50 years,

$$d = 5/50 = 0.10$$

b. Environmental conditions. Environmental conditions shall be defined for the ambient service of the equipment. An approximate approach (Greene and Bourne 1972) multiplies failure data by various K factors to relate the data to other conditions of environment and stress. Typical K factors are given in Table C-1 where K_1 relates to the general environment of operation, K_2 to the specific rating or stress of the component, and K_3 to the general effect of temperature. The equipment on the lock is considered to be exposed to an outdoor marine environment. For this example, a K_1 factor of 2 is used and K_2 and K_3 are 1.0.

Table C-1
Overall Environment - Component Stress Levels
(Greene and Bourne 1972)

General Environmental Condition	K_1
Ideal, static conditions	0.1
Vibration-free, controlled environment	0.5
General-purpose, ground-based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0

Stress Rating

Percentage of component nominal rating	K_2
140	4.0
120	2.0
100	1.0
80	0.6
60	0.3
40	0.2
20	0.1

Temperature

Component temperature (degrees C)	K_3
0	1.0
20	1.0
40	1.3
60	2.0
80	4.0
100	10.0
120	30.0

Other data sources such as “NPRD Nonelectronic Parts Reliability Data” (Reliability Analysis Center 1994) also contain environmental information.

c. *Lock equipment reliability*. The Weibull distribution was used to perform the reliability analysis for each component in the block diagram. The values for β were selected from the values given in Table 7-2 of Bloch and Geitner (1994) and reproduced as Table C-6, by choosing a dominant failure mode for each component. If β cannot be determined, a value of 1.0 should be used. It should be noted that most of the β values in Table C-6 are greater than or equal to 1.0, but not greater than 3.0. These values represent random and wear-out failures as indicated by Regions B and C of the bathtub curve. The characteristic life parameter α is determined from the failure rate data. Table C-7 contains failure rates for several common mechanical components found on locks and dams. While α is normally determined through experimental methods, it can be approximated from the ratio of α/MTTF as a function of β by using Table C-2. For example, the dominant failure mechanism for the spur gears is considered to be wear such as fretting, scoring, or pitting. From Table C-6, the shape parameter β (Weibull Index) is 3.0, and from Table C-2 α/MTTF = 1.10. The life parameter α is calculated as follows:

From the published data of Table C-7, the summary or combined failure rate (λ) computed from all individual data sources for spur gears is given as 3.2232 failures per million operating hours. The environmental factors are $K_1=2$, $K_2=K_3=1$.

The adjusted failure rate (λ') is:

$$\lambda' = \lambda K_n \tag{C-2}$$

$\lambda' = 3.2232 * K_1 * K_2 * K_3 = 6.446$ failures per million operating hours

and,

$$\text{MTTF} = 1/\lambda' \tag{C-3}$$

$$= 1/6.446 = 0.155 \text{ E6 hr}$$

therefore,

$$\alpha = \text{MTTF} * 1.1 \tag{C-4}$$

$$= 0.155 \text{ E6} * 1.1 = 0.17 \text{ E6 hr}$$

$$\alpha = 0.17\text{E6}/8760 = 19.4 \text{ years}$$

Table C-2
α/MTTF Ratio as a function of β
(Reliability Analysis Center 1994)

β	α/MTTF
1	1.00
2	1.15
2.5	1.12
3.0	1.10
4.0	1.06

The Weibull reliability function from the main text for the components becomes:

$$R(t) = \exp\left[-\left(\frac{td}{a}\right)^{b}\right] \qquad \text{(C-5)}$$

where time t is in years. The Weibull hazard function becomes:

$$h(t) = \frac{b}{a}\left(\frac{td}{a}\right)^{b-1} \qquad \text{(C-6)}$$

For this example, the electric motors were considered electrical devices and are not included in this reliability analysis. They are evaluated in the electrical analysis. The mechanical system was considered to begin at the first coupling. The reliability for the miter gate machinery model of Figure C-2 at time t is calculated as:

$$R_{SYS}(t) = R_A(t)^3 * R_B(t)^2 * R_C(t) * R_D(t) * R_E(t)^2 * R_F(t)^2 * R_G(t)^2 \qquad \text{(C-7)}$$

The reliability for the tainter valve machinery model of Figure C-4 is calculated as:

$$R_{SYS}(t) = R_A(t)^4 * R_B(t)^2 * R_C(t) * R_D(t) * R_E(t)^4 * R_F(t)^3 \qquad \text{(C-8)}$$

The tainter valve hoist drums and wire rope were not modeled because no failure data were available. Also, these items are organized in parallel so their combined reliability value is much higher than the other components.

d. Dam equipment reliability. The dam machinery block diagram is shown in Figure C-6. The system was considered a series model since the unreliability of one component will cause the entire system to be inoperable. The duty factor was determined as follows:

Assume two gate changes per day at 5 min each.

d = (2*5)min/day*365 days/yr/60/8760 hr/yr = 0.007

The dam gate system reliability calculation is similar to the lock machinery.

$$R_{SYS}(t) = R_A(t) * R_B(t)^{10} * R_C(t) * R_D(t)^4 * R_E(t)^{16} * R_F(t)^6 * R_G(t)^4 \qquad \text{(C-9)}$$

C-4. Results

a. Lock equipment. The analyses for each major component of the miter gate and tainter valve systems for 50 years of service are contained in spreadsheet format in Tables C-3 and C-4. The values in the tables are shown rounded to the nearest four decimal places; however, they are not rounded for the mathematical analysis. As a result, some components show a reliability value of 1.0 in future years when their hazard rates are nonzero. The system reliability for the miter gate and valve machinery drops to 44 and 36 percent, respectively, after 50 years. It should be noted that the brakes and the gear reducers have the highest hazard rates, which indicates a higher susceptibility to failure. The electric motors for this analysis were considered electrical equipment and are not included in the mechanical analyses.

b. Dam equipment. The results are tabulated in Table C-5. The dam machinery is 82 percent after 50 years. Failure data on the sprocket were not available and therefore were not included in the analysis.

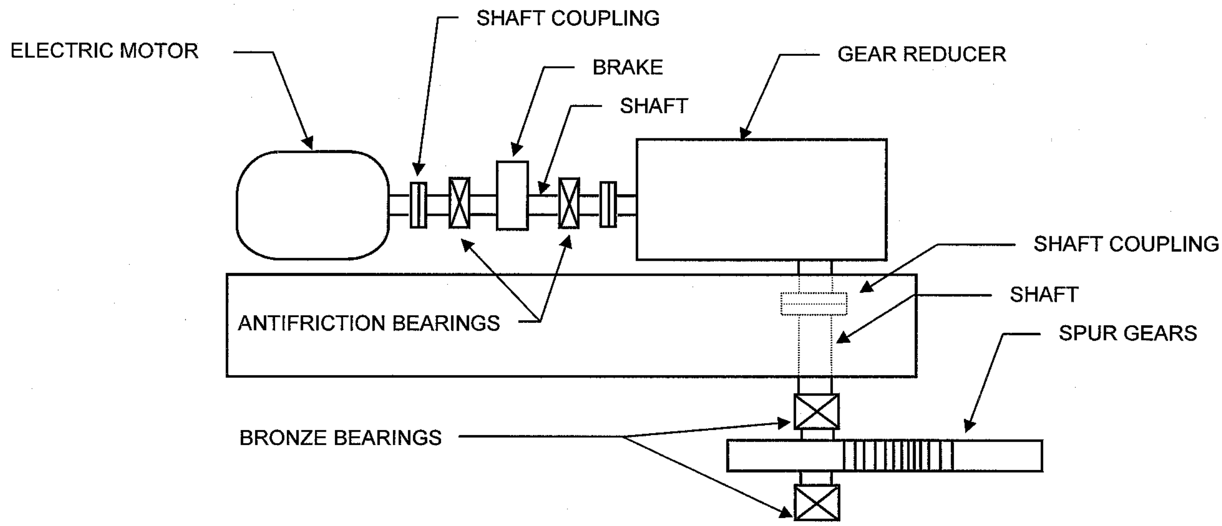
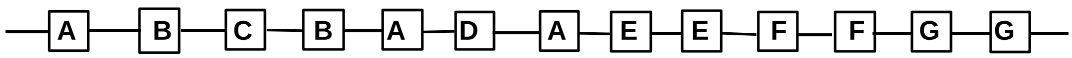


Figure C-1. Miter gate machinery



A - COUPLING
B - ANTIFRICTION BEARING
C - BRAKE
D - GEAR REDUCER
E - PLAIN BRONZE BEARING
F - SPUR GEAR
G - SHAFT

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts.

Figure C-2. Lock machinery basic and mission reliability diagram

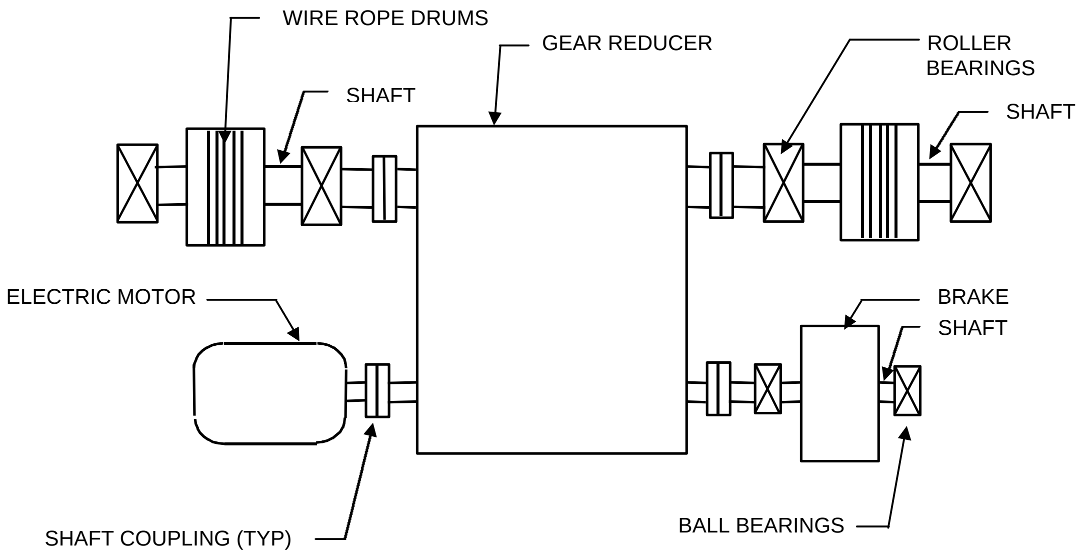
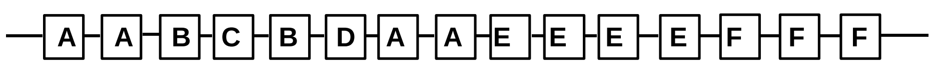


Figure C-3. Tainter valve machinery



A - SHAFT COUPLING
B - BALL BEARING
C - BRAKE
D - GEAR REDUCER
E - ROLLER BEARING
F - SHAFT

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts, and hoist drums and wire rope.

Figure C-4. Valve machinery basic and mission reliability diagram

Table C-3
Reliability Analysis Lock Miter Gate Machinery

Component/Block	Quan.	Failure Rate[1]	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α,Yrs	Duty Factor, d
Couplings	3	1.4054	misalignment	1.0	1.00	2	40.6131	0.1
Antifriction Bearing	2	1.6445	wear	3.0	1.10	2	38.1790	0.1
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798	0.1
Gear Reducer	1	5.0000	wear	3.0	1.10	2	12.5571	0.1
Plain Bronze Bearings	2	2.3811	wear	3.0	1.10	2	26.3682	0.1
Spur Gears	2	3.2232	wear	3.0	1.10	2	19.4792	0.1
Shafts	2	0.9298	fracture	1.0	1.00	2	61.3870	0.1

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	1.0000	0.9878	0.9757	0.9637	0.9519	0.9403	0.9288	0.9174	0.9062	0.8951	0.8842
Antifriction Bearings	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9995	0.9992	0.9989	0.9984	0.9978
Brake	1.0000	0.9818	0.9639	0.9463	0.9291	0.9121	0.8955	0.8792	0.8631	0.8474	0.8320
Gear Reducer	1.0000	0.9999	0.9995	0.9983	0.9960	0.9921	0.9865	0.9786	0.9682	0.9550	0.9388
Plain Bronze Bearings	1.0000	1.0000	0.9999	0.9998	0.9996	0.9991	0.9985	0.9977	0.9965	0.9950	0.9932
Spur Gears	1.0000	1.0000	0.9999	0.9995	0.9989	0.9979	0.9964	0.9942	0.9914	0.9877	0.9832
Shafts	1.0000	0.9919	0.9838	0.9759	0.9679	0.9601	0.9523	0.9446	0.9369	0.9293	0.9218

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Antifriction Bearings	0.0000	0.0000	0.0001	0.0001	0.0002	0.0003	0.0005	0.0007	0.0009	0.0011	0.0013
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Gear Reducer	0.0000	0.0004	0.0015	0.0034	0.0061	0.0095	0.0136	0.0186	0.0242	0.0307	0.0379
Plain Bronze Bearings	0.0000	0.0000	0.0002	0.0004	0.0007	0.0010	0.0015	0.0020	0.0026	0.0033	0.0041
Spur Gears	0.0000	0.0001	0.0004	0.0009	0.0016	0.0025	0.0037	0.0050	0.0065	0.0082	0.0101
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [$R_{svs}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9308	0.8657	0.8042	0.7454	0.6890	0.6347	0.5823	0.5316	0.4826	0.4355

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994)

Table C-4
Reliability Analysis Lock Tainter Valve Machinery

Component/Block	Quan.	Failure Rate[1]	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α,Yrs	Duty Factor, d
Couplings	4	1.4054	misalignment	1.0	1.00	2	40.6131	0.1
Ball Bearing	2	1.6445	wear	3.0	1.10	2	38.1790	0.1
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798	0.1
Gear Reducer	1	5.0000	wear	3.0	1.10	2	12.5571	0.1
Roller Bearings	4	2.8201	wear	3.0	1.10	2	22.2635	0.1
Shafts	3	0.9298	fracture	1.0	1.00	2	61.3870	0.1
Wire Rope Drums	2	Information not Available						

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

	Years in Service (Equipment is installed at time 0)										
	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	1.0000	0.9878	0.9757	0.9637	0.9519	0.9403	0.9288	0.9174	0.9062	0.8951	0.8842
Ball Bearing	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9995	0.9992	0.9989	0.9984	0.9978
Brake	1.0000	0.9818	0.9639	0.9463	0.9291	0.9121	0.8955	0.8792	0.8631	0.8474	0.8320
Gear Reducer	1.0000	0.9999	0.9995	0.9983	0.9960	0.9921	0.9865	0.9786	0.9682	0.9550	0.9388
Roller Bearings	1.0000	1.0000	0.9999	0.9997	0.9993	0.9986	0.9976	0.9961	0.9942	0.9918	0.9887
Shafts	1.0000	0.9919	0.9838	0.9759	0.9679	0.9601	0.9523	0.9446	0.9369	0.9293	0.9218

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Ball Bearing	0.0000	0.0000	0.0001	0.0001	0.0002	0.0003	0.0005	0.0007	0.0009	0.0011	0.0013
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Gear Reducer	0.0000	0.0004	0.0015	0.0034	0.0061	0.0095	0.0136	0.0186	0.0242	0.0307	0.0379
Roller Bearings	0.0000	0.0001	0.0003	0.0006	0.0011	0.0017	0.0024	0.0033	0.0043	0.0055	0.0068
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [R_{sys}(t)]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9119	0.8311	0.7563	0.6869	0.6222	0.5617	0.5050	0.4518	0.4021	0.3557

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994)

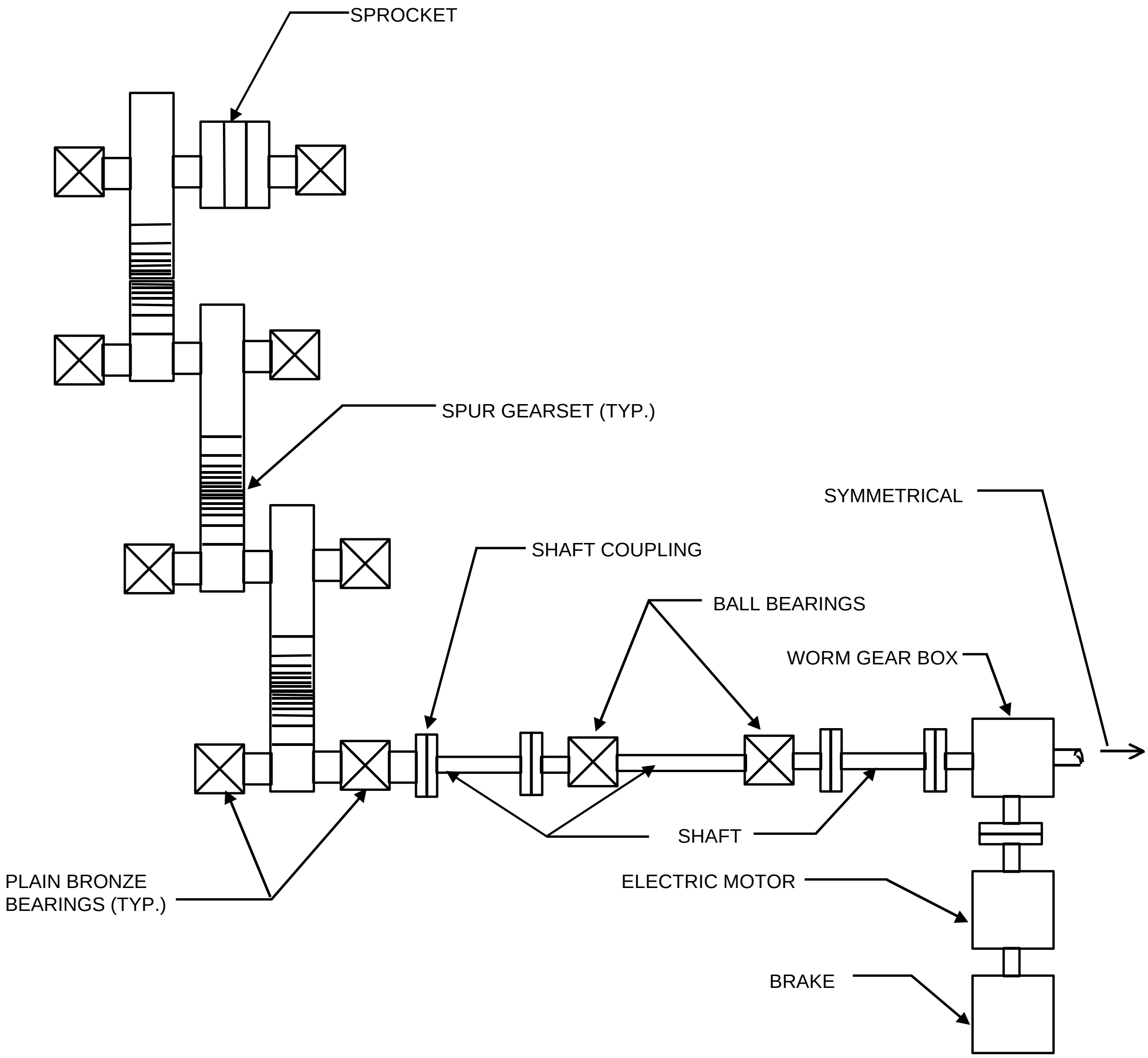


Figure C-5. Dam gate machinery

A - BRAKE
B - SHAFT COUPLING
C - WORM GEAR BOX
D - BALL BEARINGS
E - PLAIN BRONZE BEARINGS
F - SPUR GEARSET
G - SHAFTS

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts, and chain sprocket.

Figure C-6. Dam machinery basic and mission reliability diagram

Table C-5
Reliability Analysis Dam Gate Machinery

Component/Block	Quan.	Failure Rate[1]	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α,Yrs	Duty Factor, d
Couplings	10	1.4054	misalignment	1.0	1.00	2	40.6131	0.007
Ball Bearing	4	1.6445	wear	1.0	1.00	2	34.7082	0.007
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798	0.007
Worm Gear Box	1	5.0000	wear	3.0	1.10	2	12.5571	0.007
Plain Bronze Bearings	16	2.8201	wear	3.0	1.10	2	22.2635	0.007
Spur Gearset	6	3.2232	wear	3.0	1.10	2	19.4792	0.007
Shafts	4	0.9298	fracture	1.0	1.00	2	61.3870	0.007
Sprocket	2	Information not Available						

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50	63
Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
Couplings	1.0000	0.9991	0.9983	0.9974	0.9966	0.9957	0.9948	0.9940	0.9931	0.9923	0.9914	0.9892
Ball Bearing	1.0000	0.9990	0.9980	0.9970	0.9960	0.9950	0.9940	0.9930	0.9920	0.9910	0.9900	0.9874
Brake	1.0000	0.9987	0.9974	0.9961	0.9949	0.9936	0.9923	0.9910	0.9898	0.9885	0.9872	0.9839
Worm Gear Reducer	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Spur Gearset	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Plain Bronze Bearings	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Shafts	1.0000	0.9994	0.9989	0.9983	0.9977	0.9972	0.9966	0.9960	0.9954	0.9949	0.9943	0.9928

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Ball Bearing	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Worm Gear Reducer	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003
Spur Gearset	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Plain Bronze Bearings	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM **[R_{sys}(t)]**

Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
	1.0000	0.9839	0.9681	0.9525	0.9372	0.9221	0.9072	0.8926	0.8782	0.8641	0.8502	0.8149

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994)

Table C-6
Primary Machinery Component Failure Modes
(Bloch and Geitner 1994)

Failure Mode	Weibull Index β	Standard Life
Deformation		
Brinelling	1.0	Inf
Cold flow	1.0	Inf
Contracting	2.0	Inf
Creeping	2.0	Inf
Bending	1.0	Inf
Bowing	1.0	Inf
Buckling	1.0	Inf
Bulging	1.0	Inf
Deformation	1.0	Inf
Expanding	1.0	Inf
Extruding	1.0	Inf
Growth	1.0	Inf
Necking	1.0	Inf
Setting	2.0	Inf
Shrinking	2.0	Inf
Swelling	3.0	Inf
Warping	1.0	Inf
Yielding	1.0	Inf
Examples:		
Deformation of springs	1.0	Inf
Extruding of elastomeric seals	1.0	4.0Y
Force-induced deformation	1.0	Inf
Temperature-induced deformation	2.0	Inf
Yielding	1.0	Inf
Fracture/Separation		
Blistering	1.0	Inf
Brittle fracture	1.0	Inf
Checking	1.0	Inf
Chipping	1.0	Inf
Cracking	1.0	Inf
Caustic Cracking	1.0	Inf
Ductile rupture	1.0	Inf
Fatigue fracture	1.0	Inf
Flaking	1.0	Inf
Fretting fatigue cracking	1.0	Inf
Heat checking	1.0	Inf
Pitting	1.0	Inf
Spalling	1.0	Inf
Splitting	1.0	Inf

(Continued)

Table C-6 (Continued)

Failure Mode	Weibull Index β	Standard Life
Examples:		
Overload fracture	1.0	Inf
Impact fracture	1.0	Inf
Fatigue fracture	1.1	Inf
Most fractures	1.0	Inf
Change of Material Quality		
Aging	3.0	5.0Y
Burning	1.0	Inf
Degradation	2.0	3.0Y
Deterioration	1.0	Inf
Discoloration	1.0	Inf
Disintegration	1.0	Inf
Embrittlement	1.0	Inf
Hardening	1.0	Inf
Odor	1.0	Inf
Overheating	1.0	Inf
Softening	1.0	Inf
Examples:		
Degradation of mineral oil based lubricant	3.0	1.5Y
Degradation of coolants	3.0	1.0Y
Elastomer aging	1.0	4.0-16Y
O-Ring deterioration	1.0	2.0-5Y
Aging of metals under thermal stress	3.0	4.0Y
Corrosion		
Exfoliation	3.0	2.0-4.0Y
Fretting Corrosion	2.0	3.0Y
General Corrosion	2.0	1.0-3.0Y
Intergranular Corrosion	2.0	1.0-3.0Y
Pitting Corrosion	2.0	1.0-3.0Y
Rusting	2.0	0.5-3.0Y
Staining	2.0	0.5-3.0Y
Examples:		
Accessible Components	2.0	2.0-4.0Y
Inaccessible Components	2.0	2.0-4.0Y
Wear		
Abrasion	3.0	0.5-3.0Y
Cavitation	3.0	0.5-3.0Y
Corrosive Wear	3.0	0.5-3.0Y
Cutting	3.0	0.5-3.0Y
Embedding	3.0	0.5-3.0Y

(Continued)

Table C-6 (Continued)

Failure Mode	Weibull Index β	Standard Life
Erosion	3.0	3.0Y
Fretting	3.0	2.0Y
Galling	3.0	2.0Y
Grooving	3.0	2.0Y
Gouging	3.0	2.0Y
Pitting	3.0	1.0Y
Ploughing	3.0	1.0Y
Rubbing	3.0	3.0Y
Scoring	3.0	3.0Y
Scraping	3.0	0.5-3.0Y
Scratching	3.0	3.0Y
Scuffing	3.0	1.0Y
Smearing	3.0	1.0Y
Spalling	3.0	0.5-16Y
Welding	3.0	0.5-3.0Y
Examples:		
Non-lubed relative movement	3.0	1.0Y
Contaminated by lubed sleeve bearings	3.0	3.0M
Spalling of antifriction	3.0	4.0-16Y
Bearings	1.1	16.0Y
Displacement/seizing/adhesion		
Adhesion	1.0	Inf
Clinging	1.0	Inf
Binding	1.0	Inf
Blocking	1.0	Inf
Cocking	1.0	Inf
Displacement	1.0	Inf
Freezing	1.0	Inf
Jamming	1.0	Inf
Locking	1.0	Inf
Loosening	1.0	Inf
Misalignment	1.0	Inf
Seizing	1.0	Inf
Setting	1.0	Inf
Sticking	1.0	Inf
Shifting	1.0	Inf
Turning	1.0	Inf
Examples:		
Loosening (locking fasteners)	1.0	Inf
Loosening (bolts)	1.0	Inf

(Continued)

Table C-6 (continued)

Failure Mode	Weibull Index β	Standard Life
Loosening	1.0	Inf
Misalignment (process pump set)	2.0	1.5-3.0Y
Seizing (linkages)	1.0	Inf
Seizing (components subject to contamination or corrosion)	1.0	Inf
Shifting (unstable design)	1.0	Inf
Leakage		
Joints with relative movement	1.5	3.0M-4.0Y
Joints without relative movement	1.0	16.0Y
Mechanical seal faces	0.7-1.1	0.5-1.5Y
Contamination		
Clogging	1.0	Inf
Coking	2.0	0.5-3.0Y
Dirt accumulation	2.0	0.5M-3.0Y
Fouling	1.0	Inf
Plugging	1.0	Inf
Examples:		
Fouling gas compressor	3.0	1.5-5.0Y
Plugging of passages with moving medium	1.0	Inf
Plugging of passages with non-moving medium	1.0	Inf
Conductor Interruption		
Flexible cable	1.0	Inf
Solid cable	1.0	Inf
Burning through Insulation		
Motor windings	1.0	16Y
Transformer windings	1.0	16Y

Legend: Inf = Infinite
M = Month(s)
Y = Year(s)

Table C-7
Failure Rate Data of Mechanical Components

Component[1]	Failure Rate per E6 Operating Hr
Bearings (Summary)	2.9151
Ball (Summary)	1.6445
Roller (Summary)	2.8201
Sleeve (Summary)	2.3811
Couplings, Shaft (Summary)	1.0038
Flexible	1.4054
Rigid	2.6347
Shafts (Summary)	0.9298
Gear Box (Summary)	8.7082
Reducer, Worm	5.0000
Reducer, Spiral Bevel	5.0000
Gear Train (Summary)	3.4382
Gear, Spur	3.2232
Gear, Helical	2.6008
Gear, Worm	3.8258
Gear, Bevel	1.4722
Gear, Rack	1.7562
Brake, Assembly	2.1000
Brake, Electromechanical	10.6383
Hydraulic Cylinder	0.0080
Valves	
Ball (Summary)	0.2286
Butterfly (Summary)	0.2900
Check (Summary)	0.0773
Gate (Summary)	0.0478
Globe (Summary)	0.1439
Hydraulic (Summary)	8.8292
Ball	2.3841
Bellows Diaphragm	14.8953
Check	5.3725
Control	57.7196
Relief	0.9201
Solenoid	25.0590
Seal (Summary)	5.4715
Packing	3.5308
O-ring	4.6511
Gaskets (Summary)	0.0195

(Continued)

[1] Failure Rates are from NPRD Data (1995) (Reliability Analysis Center 1994). The data including the summary data represents combined failure rate data which is a weighted merger of several failure rates.

Table C-7 (Concluded)

Component	Failure Rate per E6 Operating Hr
Springs (Summary)	0.6134
Pump	
Hydraulic (Summary)	46.9604
Centrifugal	10.4022
Fixed Displacement	1.4641
Positive Displacement	9.5620
Motor Driven	12.9870
Variable Delivery	54.0498
Centrifugal	51.1732
Piping (Summary)	0.4734

APPENDIX D: ELECTRICAL EQUIPMENT EXAMPLE

D-1. Description

The electrical one-line diagram of the example lock and dam electrical system is shown in Figure D-1. The mission reliability electrical subsystems were extracted from Appendix B. Several of the electrical blocks from Appendix B did not have failure rate data readily available. These blocks required further extrapolation to the extent that available failure rate data were available.

D-2. Mission Reliability

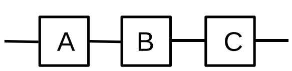
The normal electrical service (LAl) was arranged into a series-connected block diagram which included the utility power supply, underground cables in duct, and a main circuit breaker as shown in Figure D-2. The resulting equation is:

$$R_{SYS}(t) = R_A(t)*R_B(t)*R_C(t) \qquad \text{(D-1)}$$

The standby service (LA2) was broken down into a series block diagram of the standby generator and underground cables in duct as shown in Figure D-3. The resulting equation is:

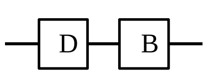
$$R_{SYS}(t) = R_D(t)*R_B(t) \qquad \text{(D-2)}$$

The automatic transfer switch (LB) and switchboard (LC) did not require additional refinement in the diagram because the reliability information for these items was readily available directly in published sources (Reliability Analysis Center 1994)



A - Utility power supply
B - Underground cables in duct
C - Main circuit breaker

Figure D-2. Electrical service (LA1) block diagram

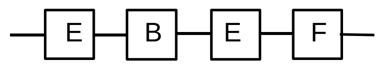


D - Standby Generator

Figure D-3. Standby service (LA2) block diagram

The dam feeders and each of the lock gates and valves obtain their power from the switchboard located in the central control station. The two feeder blocks (DD1 and DD2) were connected in parallel to designate the redundancy of this subsystem. Each feeder was diagrammed as a series of blocks representing a molded case circuit breaker, underground cables in duct, another molded case circuit breaker, and aboveground cables in conduit, respectively, as shown in Figure D-4. The resulting equation is:

$$R_{SYS}(t) = R_E(t)*R_B(t)*R_E(t)*R_F(t) \qquad \text{(D-3)}$$



E - Circuit breaker
F - Aboveground cables in conduit

Figure D-4. Dam feeder (DD1 and DD2) block diagram

Each lock gate (LD1, LD2, LD3, LD4) electrical equipment of Appendix B was extrapolated into appropriate components as a unique parallel-series block diagram. The diagram is shown in Figure D-5. The resulting equation is:

$$R_{SYS}(t) = R_M(t) * \{1 - [1 - (R_N(t)* R_O(t)* R_P(t)* R_Q(t))] * [1 - (R_R(t)* R_S(t)* R_T(t)* R_U(t))]\} \qquad \text{(D-4)}$$

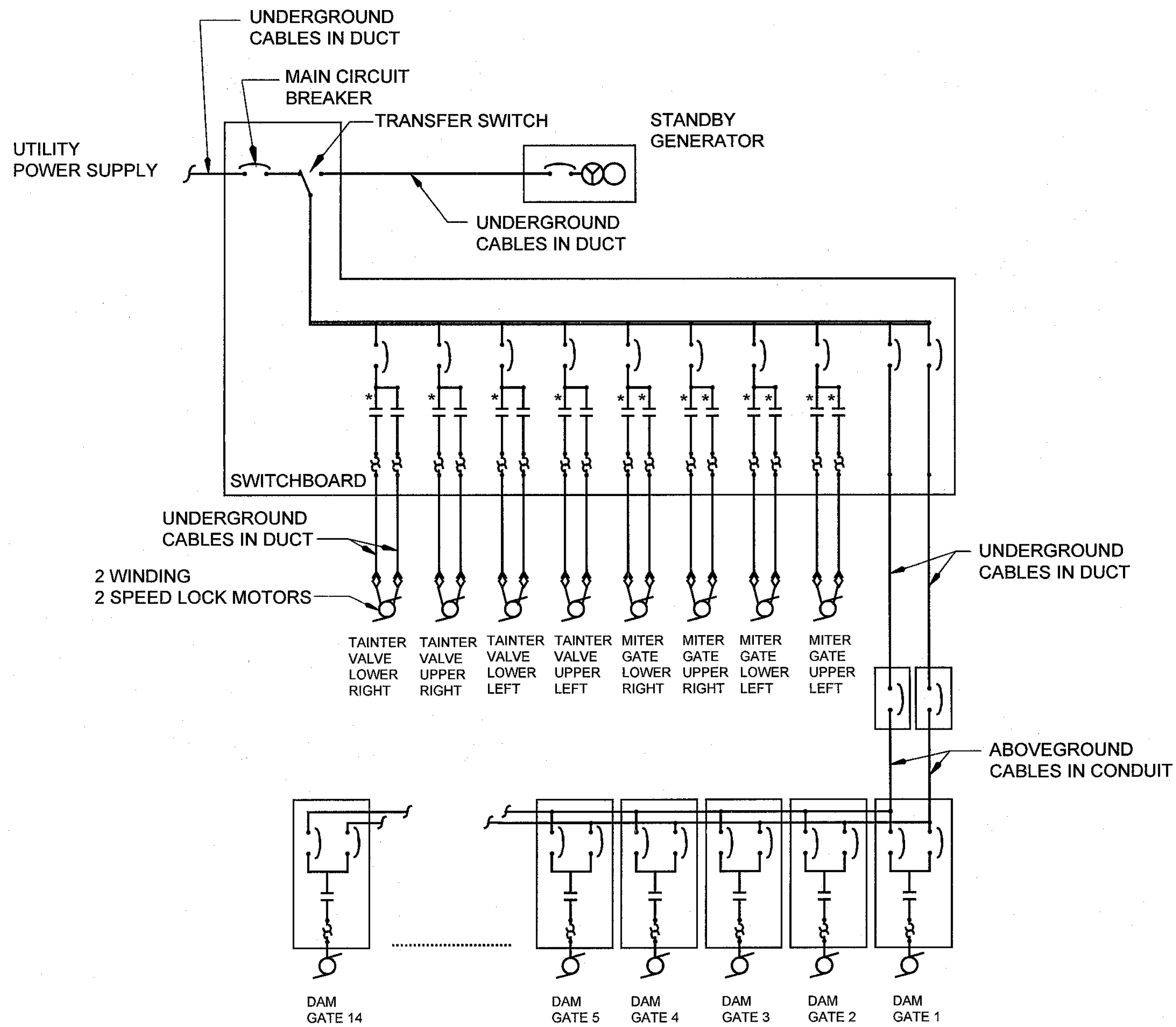
The lock valve (LE1, LE2, LE3, LE4) electrical equipment was similar except the valves do not have slow speed reverse starter (O). (See Figure D-6.) The resulting equation is:

$$R_{SYS}(t) = R_M(t) * \{1 - [1 - (R_N(t)* R_P(t)* R_Q(t))] * [1 - (R_R(t)* R_S(t)* R_T(t)* R_U(t))]\} \qquad \text{(D-5)}$$

The dam gate (DE1 through 14) electrical equipment was similar except the gates do not have slow speed starters, conductors, or windings (N, O, P, Q) and have parallel redundant circuit breakers (M). (See Figure D-7.)

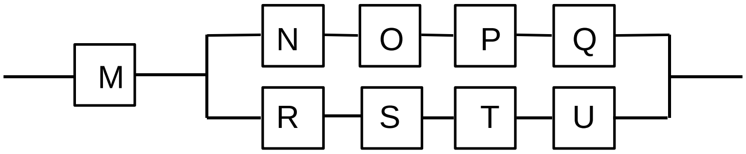
The resulting equation is:

$$R_{SYS}(t) = \{2*R_M(t)- [R_M(t)*R_M(t)]\}*R_R(t)*R_S(t)*R_T(t)* R_U(t) \qquad \text{(D-6)}$$



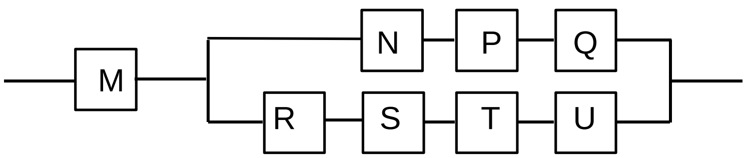
* Forward and Reverse Starters

Figure D-1. Lock and dam electrical one-line diagram



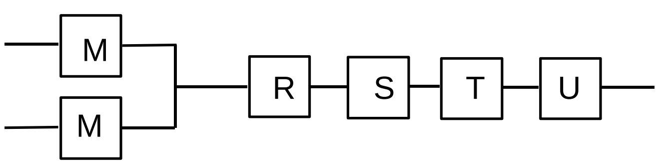
M - Circuit breaker
N – Slow-speed starter
O – Slow-speed reverse starter
P – Slow-speed conductors to motor
Q - Motor low-speed windings
R – Fast-speed forward starter
S – Fast-speed reverse starter
T – Fast-speed conductors to motor
U - Motor fast-speed windings

Figure D-5. Lock gate (LD) electrical mission reliability block diagram



M - Circuit breaker
N – Slow-speed starter
P – Slow-speed conductors to motor
Q - Motor low-speed windings
R – Fast-speed forward starter
S – Fast-speed reverse starter
T – Fast-speed conductors to motor
U - Motor fast-speed windings

Figure D-6. Lock valve (LE) electrical mission reliability block diagram



M - Circuit breaker
R – Fast-speed forward starter
S - Fast-speed reverse starter
T – Fast-speed conductors to motor
U - Motor fast-speed windings

Figure D-7. Dam gate (DE) electrical mission reliability block diagram

a. Environmental conditions. The environmental conditions were considered for the ambient service of the electrical equipment. Determination of the environmental K factor was the same as for the mechanical equipment. (See Appendix C, Paragraph C-3c.) The electrical equipment on the lock and dam was considered to be exposed to an outdoor marine environment resulting in a K_1 factor of 2.

b. Failure rate. The failure rates of all applicable components were obtained from the published literature (Reliability Analysis Center 1994 and ANSI/IEEE Std 493-1980). Typical component failure rates from two sources are provided in Tables D-1 and D-2. The typical failure rates were adjusted in the analysis to the environmental conditions of the lock.

$$\lambda' = \lambda K \qquad \text{(D-7)}$$

where

λ = typical failure rate
K = environmental factor = 2
λ' = adjusted failure rate

c. Duty cycle. Failures of electrical equipment often correspond to voltage and/or current parameters. Failure rates are typically provided in "operating hours," or "experience hours," which by definition are a duration of exposure to voltage and/or current. Since voltage and current applied to equipment are near zero at times of inoperation, the total mission time was adjusted with a duty cycle factor. The duty cycle factor is the ratio of actual time the equipment is energized by voltage and/or current to the total mission time *t*.

$$t' = td \qquad \text{(D-8)}$$

where

t = calendar time variable
d = duty cycle factor
t′ = adjusted time variable
(i.e. operation time)

For example, electrical equipment such as transfer switches is normally energized 100 percent of the calendar year, resulting in a duty cycle of 1.0. If the lock gate and valve equipment have an average number of 13,148 open/close cycles per year and the operating time of an open or close cycle is assumed to be 120 sec, then

$$d = ((120 * 2)\text{sec/cycle} * 13\,148 \text{ cycles/yr}) / 31\,536\,000 \text{ sec/yr}$$

$$d = 0.10$$

Each component time variable was adjusted as applicable to its duty cycle. Even though the lock gates and valves are operated with a system duty cycle of 0.10, the duty cycle for the gate and valve electrical equipment must account for the two-speed operation. The slow speed portion of each system operation is 3 sec/120 sec, or 2.5 percent of the system duty cycle. The final duty cycle factor used to adjust the time variable for the slow-speed components of the gate and valve equipment was 0.0025 and the associated high-speed factor was 0.10-0.0025=0.0975. For forward and reverse starters, the applicable duty factor was further reduced by 50 percent to compensate for the alternating use of the starters in during a lockage cycle.

The emergency generator duty cycle was calculated assuming a maximum standard operation of 2 hr in 24 hr (0.08). The dam gates were calculated at 0.007 as demonstrated in Appendix C. The dam feeders were calculated at 0.5 assuming that each feeder is alternately energized uniformly.

d. Distribution. The modes of failure for electrical equipment are very complex (i.e. they involve a wide variety of distresses such as temperature, vibration, mechanical stresses, etc.) resulting in an inability to select β values for a Weibull distribution. Since the values were not known, a value of 1.0 was used, which reduces the Weibull distribution equation to the exponential distribution for the computation of the reliability value. The exponential reliability equation is:

$$R(t) = e^{-\lambda' t'} \qquad \text{(D-9)}$$

where

λ' = adjusted failure rate - failures/yr
t′ = adjusted time variable (operation time) – yr

D-3. Results

The results for the electrical subsystems are shown in spreadsheet format in Tables D-3 to D-7. It is evident that the lock electrical distribution reliability is much less than that of any other electrical subsystem evaluated. This was attributed to the 100 percent demand on the major components of that subsystem and also its greater failure rate.

Table D-1
NPRD-1 Electrical Component Failure Rate Data

Component[1]	Failure Rate per E6 Operating Hr
Arrester, Surge	2.6988
Cable (Summary)	1.1383
Above Ground (in conduit)	0.0300
Above Ground (no conduit)	0.4311
Aerial	0.6516
Below Ground (in duct)	0.5988
Below Ground (in conduit)	0.1876
Below Ground (direct buried)	2.5417
Capacitor Bank	4.5913
Circuit Breaker (Summary)	1.7856
Molded case	0.3574
Electric Motor (Summary)	9.2436
AC	6.8834
DC	14.4367
Fuse (Summary)	2.5012
Receptacle (Summary)	2.2727
Starter (Summary)	0.7636
Motor	0.0212
Switch, Disconnect (Summary)	4.5645
Switchgear (Summary)	0.5830
Bus (Summary)	0.5051
Bare	0.3890
Insulated	0.7925
Switch, Transfer (Summary)	6.3978

[1] The summary data represents combined failure rate data, which is merged from several different sources.

Table D-2
ANSI/IEEE Std. 493 Electrical Component Failure Rate Data

Component (Failures per Unit-Year)	Failure Rate per E6 Experience Hr
Electric utility power supplies, single circuit (0.537)	61.3014
Transformers	
Liquid-filled, all (0.0041)	0.4680
Dry-type (0.0036)	0.4110
Generator (diesel or gas-driven)	7.6500

Table D-3
Reliability Analysis Lock Electrical Distribution

Component/Block	Quan.	Failure Rate[1]	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Utility Power Supply	1	61.3014	1.0	2	122.6028	1.0000
Conductors in Duct	2	0.5988	1.0	2	1.1976	1.0000
Circuit Breaker	1	0.3574	1.0	2	0.7148	1.0000
Generator	1	7.6500	1.0	2	15.3000	0.0800
Transfer Switch	1	6.3978	1.0	2	12.7956	1.0000
Switchgear, Bus, Bare	1	0.5051	1.0	2	1.0102	1.0000

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Utility Power Supply	1.0000	0.0047	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Conductors in Duct	1.0000	0.9489	0.9004	0.8544	0.8107	0.7693	0.7300	0.6927	0.6573	0.6237	0.5918
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312
Generator	1.0000	0.9478	0.8983	0.8514	0.8070	0.7649	0.7249	0.6871	0.6512	0.6172	0.5850
Transfer Switch	1.0000	0.5710	0.3260	0.1861	0.1063	0.0607	0.0346	0.0198	0.0113	0.0064	0.0037
Switchgear, Bus, Bare	1.0000	0.9567	0.9153	0.8757	0.8378	0.8015	0.7668	0.7336	0.7019	0.6715	0.6424

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Utility Power Supply	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740
Conductors in Duct	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Generator	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340
Transfer Switch	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121
Switchgear, Bus, Bare	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088

RELIABILITY OF SYSTEM $R_{svs}(t)]$

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.8885	0.7631	0.6566	0.5649	0.4861	0.4182	0.3599	0.3096	0.2664	0.2292

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994) and IEEE Std 493, Appendix A.

Table D-4
Reliability Analysis Lock Miter Gate Electrical Equipment

Component/Block	Quan.	Failure Rate[1]	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Circuit Breaker	1	0.3574	1.0	2	0.7148	1.0000
Forward Starter, Fast	1	0.0212	1.0	2	0.0424	0.0488
Reverse Starter, Fast	1	0.0212	1.0	2	0.0424	0.0488
Conductors in Duct, Fast	1	0.5988	1.0	2	1.1976	0.0975
Electric Motor, AC, Fast	1	6.8834	1.0	2	13.7668	0.0975
Forward Starter, Slow	1	0.0212	1.0	2	0.0424	0.0013
Reverse Starter, Slow	1	0.0212	1.0	2	0.0424	0.0013
Conductors in Duct, Slow	1	0.5988	1.0	2	1.1976	0.0025
Electric Motor, AC, Slow	1	6.8834	1.0	2	13.7668	0.0025

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312
Forward Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995	0.9995	0.9994	0.9993	0.9992	0.9991
Reverse Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995	0.9995	0.9994	0.9993	0.9992	0.9991
Conductors in Duct, Fast	1.0000	0.9949	0.9898	0.9848	0.9798	0.9748	0.9698	0.9648	0.9599	0.9550	0.9501
Electric Motor, AC, Fast	1.0000	0.9429	0.8891	0.8383	0.7904	0.7453	0.7028	0.6626	0.6248	0.5891	0.5555
Forward Starter, Slow	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Reverse Starter, Slow	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Conductors in Duct, Slow	1.0000	0.9999	0.9997	0.9996	0.9995	0.9993	0.9992	0.9991	0.9990	0.9988	0.9987
Electric Motor, AC, Slow	1.0000	0.9985	0.9970	0.9955	0.9940	0.9925	0.9910	0.9895	0.9880	0.9865	0.9850

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Forward Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Fast	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Fast	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206
Forward Starter, Slow	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter, Slow	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Slow	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Slow	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206

RELIABILITY OF SYSTEM **[R_{sys}(t)]**

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9691	0.9389	0.9096	0.8810	0.8532	0.8261	0.7999	0.7744	0.7496	0.7256

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center) and IEEE Std 493, Appendix A.

Table D-5
Reliability Analysis Lock Tainter Valve Electrical Equipment

Component/Block	Quan.	Failure Rate[1]	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Circuit Breaker	1	0.3574	1.0	2	0.7148	1.0000
Forward Starter, Fast	1	0.0212	1.0	2	0.0424	0.0488
Reverse Starter, Fast	1	0.0212	1.0	2	0.0424	0.0488
Conductors in Duct, Fast	1	0.5988	1.0	2	1.1976	0.0975
Electric Motor, AC, Fast	1	6.8834	1.0	2	13.7668	0.0975
Forward Starter, Slow	1	0.0212	1.0	2	0.0424	0.0025
Conductors in Duct, Slow	1	0.5988	1.0	2	1.1976	0.0025
Electric Motor, AC, Slow	1	6.8834	1.0	2	13.7668	0.0025

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312
Forward Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995	0.9995	0.9994	0.9993	0.9992	0.9991
Reverse Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9996	0.9995	0.9995	0.9994	0.9993	0.9992	0.9991
Conductors in Duct, Fast	1.0000	0.9949	0.9898	0.9848	0.9798	0.9748	0.9698	0.9648	0.9599	0.9550	0.9501
Electric Motor, AC, Fast	1.0000	0.9429	0.8891	0.8383	0.7904	0.7453	0.7028	0.6626	0.6248	0.5891	0.5555
Forward Starter, Slow	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Conductors in Duct, Slow	1.0000	0.9999	0.9997	0.9996	0.9995	0.9993	0.9992	0.9991	0.9990	0.9988	0.9987
Electric Motor, AC, Slow	1.0000	0.9985	0.9970	0.9955	0.9940	0.9925	0.9910	0.9895	0.9880	0.9865	0.9850

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Forward Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Fast	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Fast	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206
Forward Starter, Slow	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Slow	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Slow	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206

RELIABILITY OF SYSTEM $R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9691	0.9389	0.9096	0.8810	0.8532	0.8261	0.7999	0.7744	0.7496	0.7256

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994) and IEEE Std 493, Appendix A.

Table D-6
Reliability Analysis Dam Electrical Distribution

Component/Block	Quan.	Failure Rate[1]	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Circuit Breaker	2	0.3574	1.0	2	0.7148	0.5000
Conductors in Duct	1	0.5988	1.0	2	1.1976	0.5000
Conductors in Conduit	1	0.0300	1.0	2	0.0600	0.5000

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	1.0000	0.9845	0.9692	0.9541	0.9393	0.9247	0.9104	0.8962	0.8823	0.8686	0.8551
Conductors in Duct	1.0000	0.9741	0.9489	0.9243	0.9004	0.8771	0.8544	0.8323	0.8107	0.7897	0.7693
Conductors in Conduit	1.0000	0.9987	0.9974	0.9961	0.9948	0.9935	0.9921	0.9908	0.9895	0.9882	0.9869

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Conductors in Duct	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Conductors in Conduit	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9428	0.8890	0.8382	0.7903	0.7451	0.7025	0.6624	0.6245	0.5888	0.5552

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994) and IEEE Std 493, Appendix A.

Table D-7
Reliability Analysis Dam Gate Electrical Equipment

Component/Block	Quan.	Failure Rate[1]	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Circuit Breaker	2	0.3574	1.0	2	0.7148	1.0000
Forward Starter	1	0.0212	1.0	2	0.0424	0.0035
Reverse Starter	1	0.0212	1.0	2	0.0424	0.0035
Conductors in Conduit	1	0.0300	1.0	2	0.0600	0.0070
Electric Motor, AC	1	6.8834	1.0	2	13.7668	0.0070

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

	Years in Service (Equipment is installed at time 0)											
	0	5	10	15	20	25	30	35	40	45	50	63
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2053
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312	0.6740
Forward Starter	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
Reverse Starter	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
Conductors in Conduit	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9998	0.9998	0.9998
Electric Motor, AC	1.0000	0.9958	0.9916	0.9874	0.9833	0.9791	0.9750	0.9709	0.9668	0.9627	0.9587	0.9482

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2053
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Forward Starter	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Conduit	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Electric Motor, AC	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206

RELIABILITY OF SYSTEM **[R_{sys}(t)]**

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2053
	1.0000	0.9948	0.9879	0.9794	0.9695	0.9584	0.9462	0.9331	0.9191	0.9044	0.8891	0.8471

[1] Failure rate per E6 operating hr from NPRD data, 1995 (Reliability Analysis Center 1994) and IEEE Std 493, Appendix A.